National Aeronautics and Space Administration

Neutral Atmospheric Density Modeling and the Conjunction Assessment Problem

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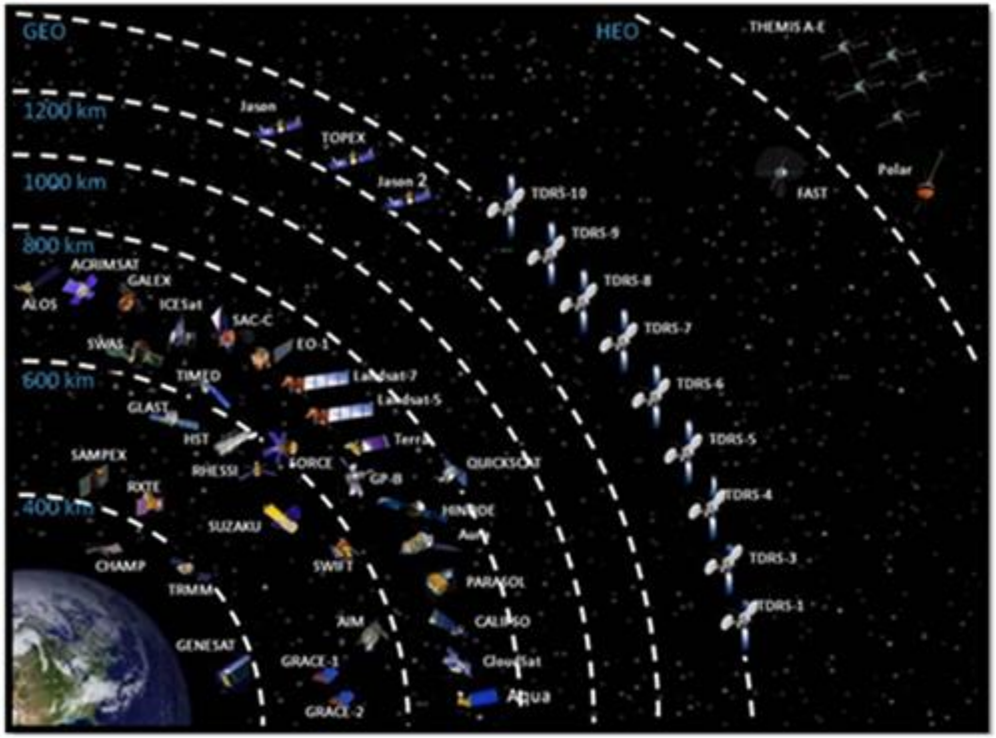
Agenda

- Conjunction Assessment (CA) introduction
- Probability of Collision (Pc) computation
- CA event canonical progression
- Pc and atmospheric drag
- JSpOC atmospheric density models
- Effect of atmospheric density mismodeling on resultant Pc
- Conjunction drag sensitivity analyses
- Conclusions

NASA Robotic Conjunction Assessment Risk Analysis (CARA)

- CARA provides conjunction risk analysis support to all <u>operational</u> NASA robotic missions
- Supports **~70** NASA missions in different orbit regimes
  - GRACE (350 km)
  - Earth Science Constellation (700 km)
  - TDRSS (GEO)
- As well as a service to other agencies
  - NOAA for POES satellites
  - USAF for SBSS and DMSP satellites

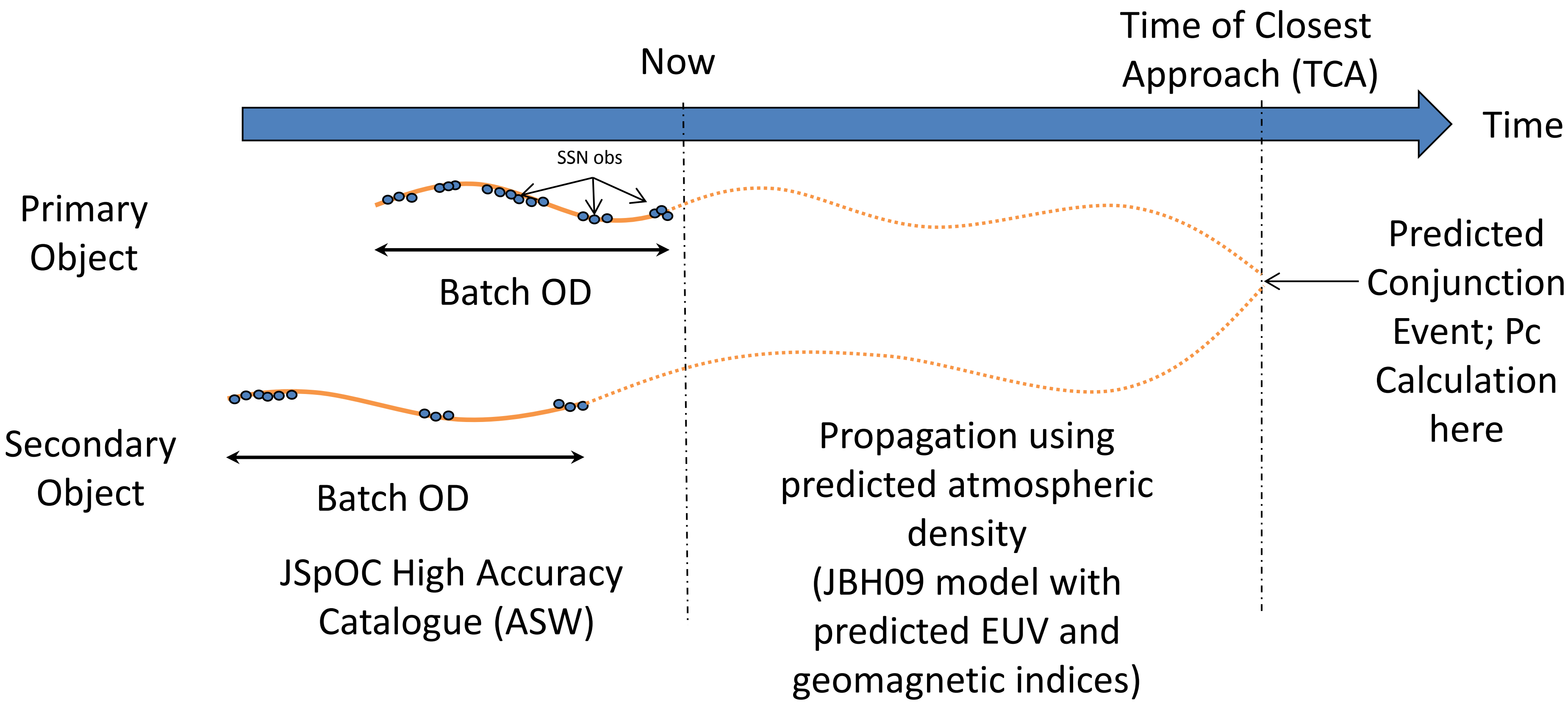


The Conjunction Assessment Risk Analysis mission at NASA GSFC is to protect NASA robotic assets from threats posed by other space objects while operating in the space environment through ensuring domain expertise, a robust concept of operations, and an operationally-responsive system to meet the expanding needs of the mission area

How are Satellite Collision Risks Determined/Mitigated?

- Certain spacecraft are determined to be “protected assets”
  - Constantly evaluated for collision risks with other objects
- For 7-10 days into the future, expected positions of each protected asset and rest of objects in the space catalogue determined
- “Keep-out volume” box drawn around the protected asset at each time-step
- Any satellite that penetrates this keep-out volume is considered a possible “conjunctor”
- Particulars of each conjunction analyzed to determine actual collision risk
  - Usually involves computing probability of collision (Pc), and other relevant parameters to give Pc proper context
- If collision risk considered too great, then mitigation actions pursued
  - Typically a risk mitigation maneuver for the protected asset

Conjunction Assessment: Process Schematic



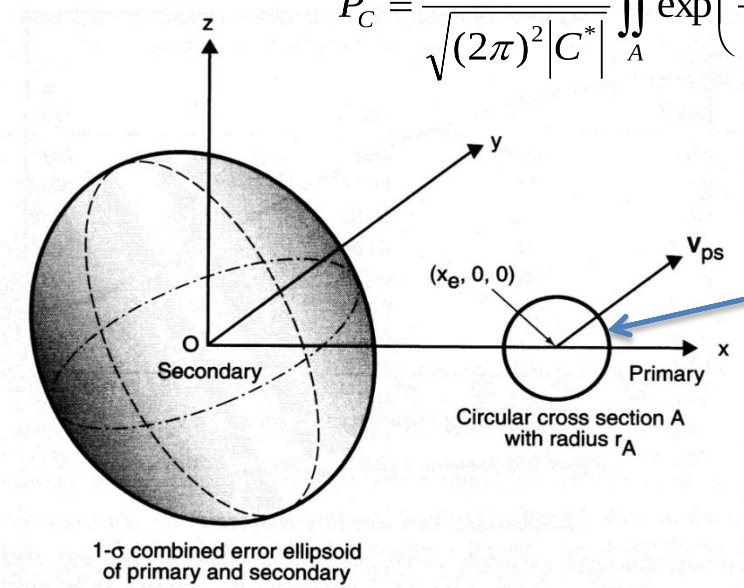
Satellite Probability of Collision: Conceptual Motivation

- Predicted trajectories at time of closest approach (TCA) give the minimum “miss distance” (MD) between the two satellites
  - If miss distance less than combined sizes of both satellites, then a collision is a real possibility
- However, uncertainties in estimates of both satellites’ positions affect meaningfulness of predicted MD
  - If uncertainties small, then estimated MD reasonable/actionable
  - If uncertainties large, then MD difficult to interpret
- Concept of “probability of collision” (Pc) thus developed
  - Likelihood that, given the uncertainties in the two satellites’ predicted trajectories, actual MD will be less than combined size
  - Satellite position uncertainty represented by covariance matrix, propagated to TCA

Satellite Probability of Collision: High-Level Calculation Explanation

- Gray ellipse is combined covariance of both objects
- Small circle has diameter of combined sizes of both objects
- Separation of circle and ellipse is nominal miss distance
- Pc is amount of covariance probability density that falls within circle
  – Computed by integral shown below

$$P_C = \frac{1}{\sqrt{(2\pi)^2 |C^*|}} \iint_A \exp\left(-\frac{1}{2} \vec{r}^{\,T} C^{*-1} \vec{r} \right) dX dZ$$



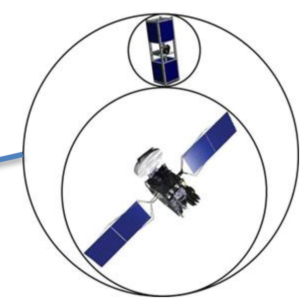
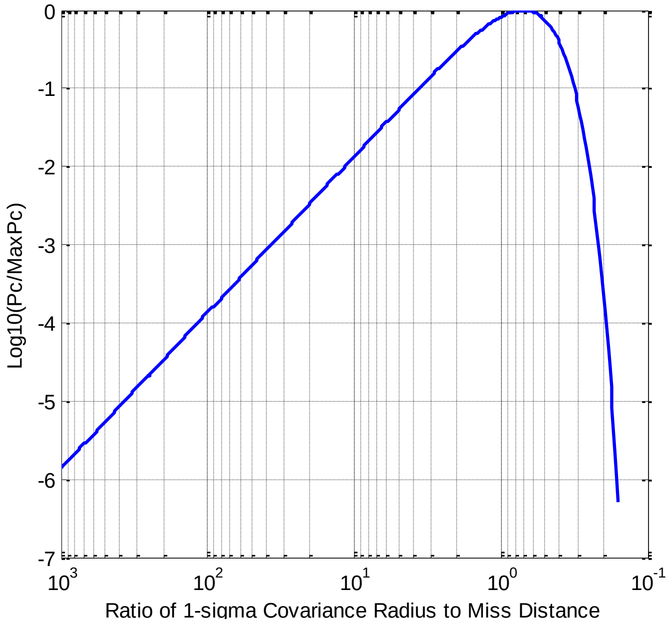


Figure taken from Chan (2008)

Conjunction Event Canonical Progression

- Conjunction usually first discovered 7 days before TCA
  - Covariances large, so typically Pc well below maximum
- As event tracked and updated, changes to state estimate are relatively small, but covariance shrinks
  - Because closer to TCA, less uncertainty in projecting positions to TCA
- Theoretical maximum Pc encountered when 1-sigma covariance size to miss distance ratio is 1/√2
  - After this, Pc usually decreases rapidly
- Behavior shown in graph at right
  - X-axis is covariance size / miss distance (related to Mahalanobus distance)
  - Y-axis is $\log_{10}(P_c/\max(P_c))$
- Improving position accuracy thus has effect on Pc that is difficult to predict
  - More accurate calculation, but Pc could increase or decrease



State Estimate Errors: Atmospheric Drag

- For LEO, atmospheric drag largest source of state estimate error
- Atmospheric drag magnitude: $a_{drag} = \frac{1}{2}\beta\rho v^2$
- Ballistic coefficient ($\beta = C_D A/M$) solved for in OD; included in covariance
- Errors in ρ can be considerable
  - In general not characterized well and not included in covariance
  - Recent effort to calculate and apply "consider parameter" to covariance to compensate for atmospheric density prediction error
- Errors in ρ become drag acceleration errors, which cause in-track (primarily) and radial (secondarily) errors in the orbit
- While state estimate accuracy desirable, probably more important to conjunction assessment to have good state error estimate
  - With this, meaningful Pc can be calculated and enable decisions
- Emphasis has been on improving models but not their error analyses

Jacchia-Bowman-HASDM-2009 Atmospheric Model

- Product of AFSPC/A9 and Solar Environment Technologies
- Built on Jacchia 70 foundation, but with updates/enhancements to many of the internal empirical models
- Employs DCA /HASDM for model debiasing during prediction interval
- Accepts frequent updates of expanded set of solar indices
  - F10, S10, M10, Y10, both short- and long-term averages
  - Uses 6-day predictions of these solar indices and employs them for propagations up to 6 days
- Also uses 3-hour Ap geomagnetic index
- Accuracy improvement of 20-45% claimed for 72-hour prediction
  - However, no within-model calculation of estimation error
- Solar storm modeling module included, using Dst parameter (next chart)

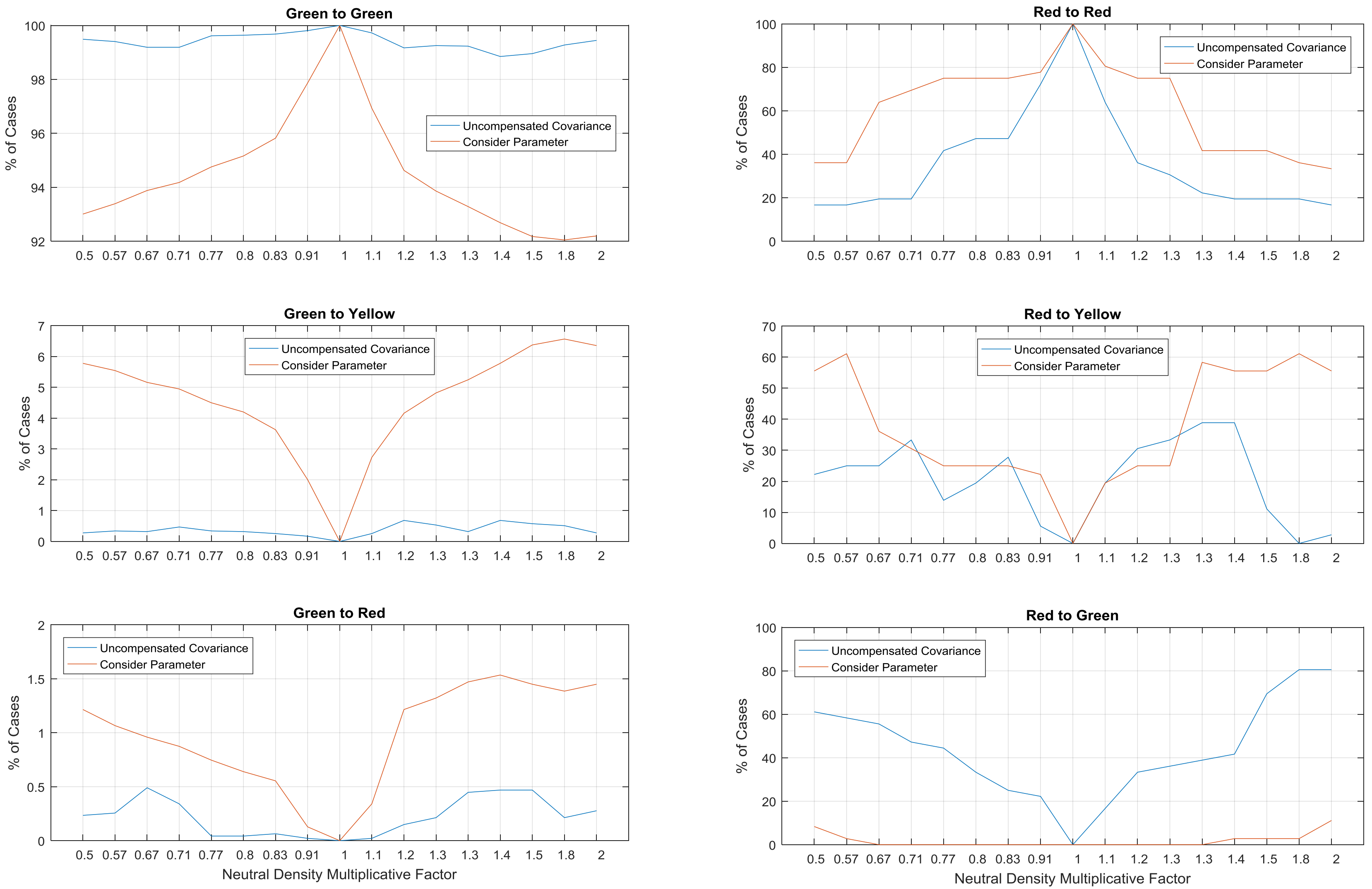
JBH09 Solar Storm Predictions

- Solar storms detected ~10 min after event, but can take 50 hours to reach Earth
  - Want to predict effects after detection, without waiting for traditional geomagnetic indices to reflect storm presence (“chasing the action”)
- JBH09 includes *Anemomilos* solar storm prediction model
  - X-ray magnitude of the flare used to determine mass of ejecta; this gives size and severity of storm
  - Flare intensity used as proxy for acceleration; integral gives storm velocity and therefore estimate of time of arrival
  - Heliolocation gives storm direction and therefore likelihood of geoeffectiveness
  - These data used to adjust neutral density estimates
    - However, no error analysis with model

Atmospheric Density Error Experiment: Effect on Calculated Pc

- Reprocess historical conjunctions, introducing error into ρ
  - Reduce and increase *ρ* by up to 100%
- Observe change in calculated Pc, in two modes
  - Covariance unaltered
  - Covariance altered to account for introduced error
    - Emulates case in which expected error in *ρ* known
- Best way to summarize results is by event “color,” which gives severity
  - Red: Pc > 1E-04; most serious event—remediation usually pursued
  - Yellow: 1E-04 < Pc < 1E-04; can become serious—event monitored
  - Green: Pc < 1E-07; event essentially ignored
- Event color changes examined as error in *ρ* introduced
- Effect on event stability if amount of *ρ* error known *a priori*

Density Error Effect on Pc: Experiment Results



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Density Error Effect on Pc: Experiment Results Interpreted

- Type I error: green events that, with error, misclassified as red
  - "False alarm" situation and therefore less worrisome case
  - Percent of affected events relatively small (only a few percent)
  - Compensated covariance produces more deviation, but at least in conservative direction
- Type II error: red events that, with error, misclassified as green
  - "Missed detection" situation and therefore more worrisome case
  - Compensated covariance pushes many of these to yellow
    - Not ideal, but event still being monitored
  - Uncompensated covariance pushes a much larger number to green
    - Much more problematic, as these events likely to be discarded
- Conclusion: density model accuracy matters significantly
  - But knowledge of model error can blunt effect substantially

Event Sensitivity to Solar Storms

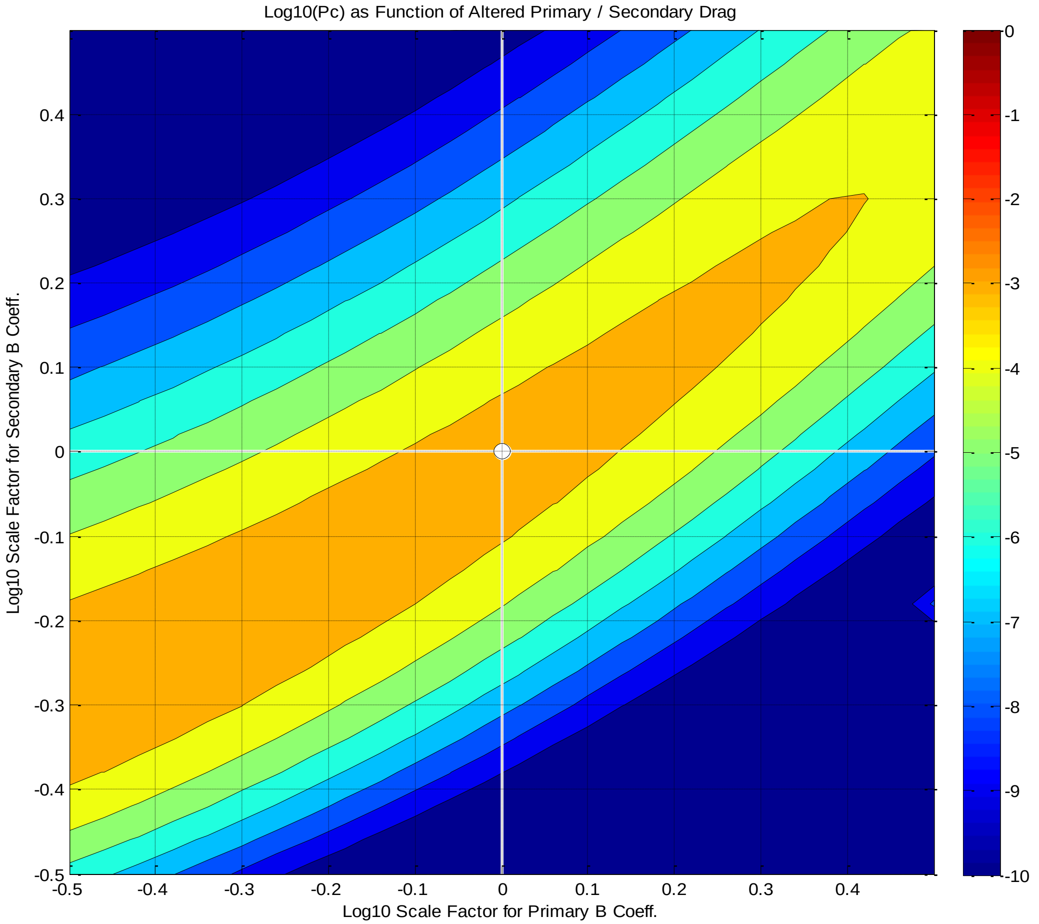
- Previously, in presence of solar storm, drag model error magnitude not known but “direction” known
  – Models did not attempt to predict solar storm effects in advance of arrival, but solar storm bound to increase drag over quiescent case
- With solar storm compensation, model error undoubtedly smaller, but direction indeterminate—could over- or under-compensate
- Thus, need to determine solution’s sensitivity to density mismodeling
- Can do this by systematically varying the ballistic coefficient
  – Density and ballistic coefficient coupled—varying one has similar effect to varying the other: $a_{drag} = \frac{1}{2}\beta\rho v^2$
  – If done systematically, can generate an entire trade-space of effects of potential density forecasting errors

The Space Weather Trade Space

- Space Weather Trade Space (SWTS) tool developed by CARA to evaluate conjunction event's sensitivity to solar storm drag mismodeling
- Ballistic coefficient for primary and secondary satellites each varied ± half an order of magnitude about the event nominal values
- Pc calculated for each pair of ballistic coefficient alterations
- Trade-space plots constructed
  - X-axis gives variation of primary satellite's ballistic coefficient
  - Y-axis gives variation of secondary satellite's ballistic coefficient
  - Contour color gives resultant Pc value
- Pc absolute values not important but contour pattern in relation to nominal value
  - Is the response contoured or flat?
  - Is the nominal value at a ridge or off the peak?

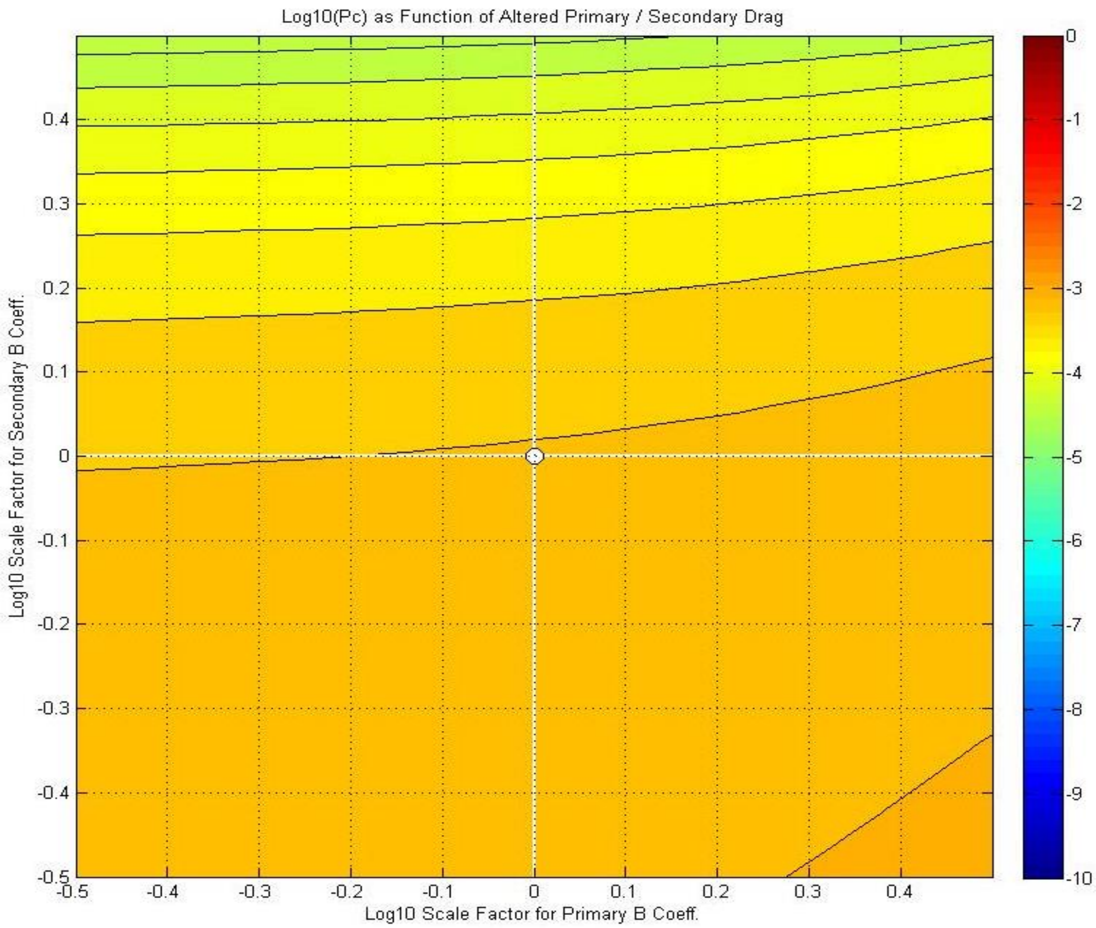
SWTS "On-ridge" Situation

- Pc on or within half an order of magnitude of highest contour
- Mis-modelling in drag will only cause Pc to decrease
- Operator can confidently make mitigation decision using these data because worst case already present



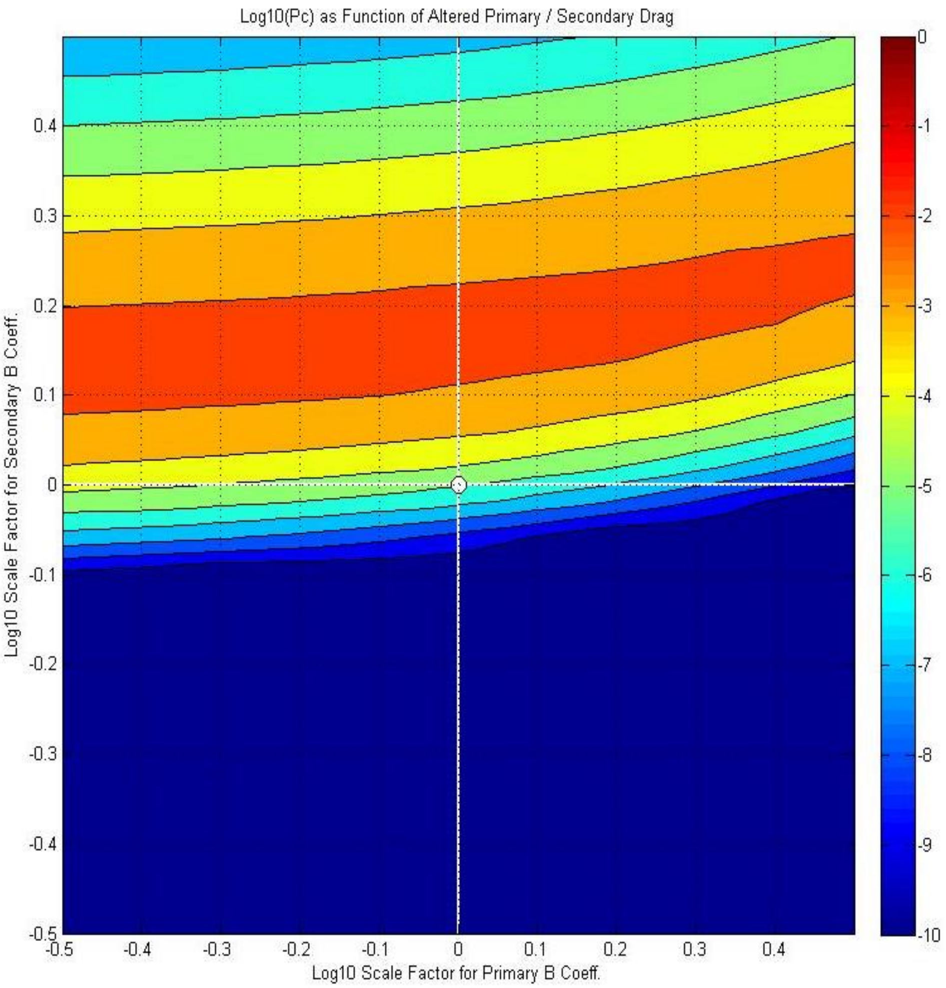
SWTS "Flat" Situation

- Pc varies less than an order of magnitude across the full trade space
- Drag mismodelling will thus have little to no effect on Pc
- Operator can confidently make mitigation decision using these data because Pc unaffected by mismodelling



SWTS "Off-peak" Situation

- Pc varies by more than an order of magnitude across the trade space
- Nominal Pc is more than half an order of magnitude from the maximum
- Density mismodelling could either increase or decrease the risk of the event
- The tool does not provide any helpful information to the Owner/Operator in this case



Conclusion

- Conjunction assessment mission substantially affected by accuracy of atmospheric modeling
  - More accurate modeling allows more actionable Pc
- However, simply knowing expected model error allows error compensation and both a correct and more stable Pc
- Important to pursue both, but accuracy improvements without error statement much less useful than if active error modeling included